

## Gravoturbulent Fragmentation

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### Abstract.

We discuss star formation in the turbulent interstellar medium. We argue that morphological appearance and dynamical evolution of the gas is primarily determined by supersonic turbulence, and that stars form via a process we call gravoturbulent fragmentation. Turbulence that is dominated by large-scale shocks or is free to decay leads to an efficient, clustered, and synchronized mode of star formation. On the other hand, when turbulence carries most of its energy on very small scales star formation is inefficient and biased towards single objects.

The fact that Galactic molecular clouds are highly filamentary can be explained by a combination of compressional flows and shear. Some filaments may accumulate sufficient mass and density to become gravitationally unstable and form stars. This is observed in the Taurus molecular cloud. Timescales and spatial distribution of protostars are well explained by the linear theory of gravitational fragmentation of filaments. The dynamical evolution, especially at late times, and the final mass distribution strongly depend on the global properties of the turbulence. In dense embedded clusters mutual protostellar interactions and competition for the available mass reservoir lead to considerable stochastic variations between the mass growth histories of individual stars.

**Key words:** ISM: clouds, ISM: kinematics, stars: formation, turbulence

### 1. Introduction

Stars form by gravoturbulent fragmentation in interstellar clouds. The supersonic turbulence ubiquitously observed in molecular gas generates strong density fluctuations with gravity taking over in the

densest and most massive regions. Once gas clumps become gravitationally unstable, collapse sets in. The central density increases until a protostellar object forms and grows in mass via accretion from the infalling envelope. Various aspects of this process have been discussed, e.g., by Hunter & Fleck (1982), Elmegreen (1993), Padoan (1995), Ballesteros-Paredes et al. (1999ab, 2003), Klessen, Heitsch, & Mac Low (2000) or Padoan & Nordlund (1999, 2002). See the reviews by Mac Low & Klessen (2003) and Larson (2003).

In this proceedings paper we discuss the complex interplay of supersonic turbulence and self-gravity and introduce the concept of gravoturbulent fragmentation. We argue that in typical star forming clouds turbulence generates the density structure in the first place and then gravity takes over in the densest and most massive regions. In Section 2 we focus on spatial distribution and timescale of star formation, then in Section 3, we discuss a specific example of a star forming filament similar to those observed in Taurus, and in Section 4 we speculate about the mass spectra of clumps and stars in the context of the gravoturbulent fragmentation model.

## 2. Spatial Distribution and Timescale of Star Formation

Supersonic turbulence plays a dual role in star formation. While it usually is strong enough to counterbalance gravity on global scales it will usually provoke collapse locally (e.g. Sasao 1973 for an early analysis; or Vázquez-Semadeni et al. 2000; Mac Low & Klessen 2003; and Larson 2003 for recent reviews). Turbulence establishes a complex network of interacting shocks, where regions of high-density build up at the stagnation points of convergent flows. These gas clumps can be dense and massive enough to become gravitationally unstable and collapse when the local Jeans length becomes smaller than the size of the fluctuation. However, the fluctuations in turbulent velocity fields are highly transient. They can disperse again once the converging flow fades away (Vazquez-Semadeni, Shadmehri, & Ballesteros-Paredes 2002). Even clumps that are strongly dominated by gravity may get disrupted by the passage of a new shock front (Klein, McKee & Colella 1994, Mac Low et al. 1994).

For local collapse to result in the formation of stars, Jeans unstable, shock-generated, density fluctuations therefore must collapse to sufficiently high densities on time scales shorter than the typical time interval between two successive shock passages. Only then do

they ‘decouple’ from the ambient flow pattern and survive subsequent shock interactions. The shorter the time between shock passages, the less likely these fluctuations are to survive. The overall efficiency of star formation depends strongly on the wavelength and strength of the driving source (Klessen et al. 2000, Heitsch, Mac Low, & Klessen 2001) which both regulate the amount of gas available for collapse on the sonic scale where turbulence turns from supersonic to subsonic (Vázquez-Semadeni, Ballesteros-Paredes, & Klessen 2003).

The velocity field of long-wavelength turbulence is dominated by large-scale shocks which are very efficient in sweeping up molecular cloud material, thus creating massive coherent structures. These exceed the critical mass for gravitational collapse by far, because the velocity dispersion within the shock compressed region is much smaller than in the ambient turbulent flow. The situation is similar to localized turbulent decay, and quickly a cluster of protostellar cores builds up. Both decaying and large-scale turbulence lead to a *clustered* mode of star formation. Prominent examples are the Trapezium Cluster in Orion with a few thousand young stars, but also the Taurus star forming region which is historically considered as a case of isolated stellar birth. Its stars, however, have formed almost simultaneously within several coherent filaments which apparently are created by external compression (see Ballesteros-Paredes et al. 1999). This renders it a clustered star forming region in the sense of the above definition.

The efficiency of turbulent fragmentation is reduced if the driving wavelength decreases. There is less mass at the sonic scale and the network of interacting shocks is very tightly knit. Protostellar cores form independently of each other at random locations throughout the cloud and at random times. There are no coherent structures with multiple Jeans masses. Individual shock generated clumps are of low mass and the time interval between two shock passages through the same point in space is small. Hence, collapsing cores are easily destroyed again. Altogether star formation is inefficient. This scenario then corresponds to an *isolated* mode of star formation. Stars that truly form in isolation are, however, very rarely observed – most young stars are observed in clusters or at most loose aggregates. From a theoretical point of view, there is no fundamental dichotomy between these two modes of star formation, they rather define the extreme ends in the continuous spectrum of the properties of turbulent molecular cloud fragmentation.

Altogether, we call this intricate interaction between turbulence on the one side and gravity on the other – which eventually leads to the transformation of some fraction of molecular cloud material into stars as described above – *gravoturbulent fragmentation*. To give an example, we discuss in detail the gravitational fragmentation in a shock-produced filaments that closely resembles structures observed in the Taurus star forming region.

### 3. Gravitational Fragmentation of a Filament in a Turbulent Flow

In Taurus, large-scale turbulence is thought to be responsible for the formation of a strongly filamentary structure (e.g. Ballesteros-Paredes et al. 1999). Gravity within the filaments should then be considered as the main mechanism for forming cores and stars. Following earlier ideas by Larson (1985), Hartmann (2002) has shown that the Jeans length within a filament, and the timescale for it to fragment are given by

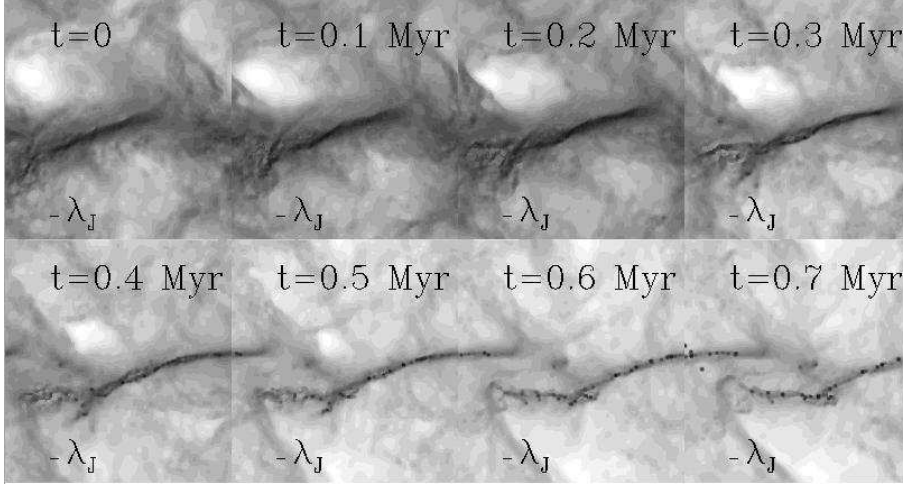
$$\lambda_J = 1.5 T_{10} A_V^{-1} \text{ pc}, \quad (1)$$

$$\tau \sim 3.7 T_{10}^{1/2} A_V^{-1} \text{ Myr}. \quad (2)$$

where  $T_{10}$  is the temperature in units of 10 K, and  $A_V$  is the visual extinction through the center of the filament. By using a mean visual extinction for starless cores of  $A_V \sim 5$  (Onishi et al. 1998), equation 1 gives a characteristic Jeans length of  $\lambda_J \sim 0.3 \text{ pc}$ , and collapse should occur in about 0.74 Myr. Indeed, Hartmann (2002) finds 3 – 4 young stellar objects per parsec which agrees well with the above numbers from linear theory of gravitational fragmentation of filaments.

In order to test these ideas, we resort to numerical simulations. We analyze a SPH calculation (Benz 1990, Monaghan 1992) of a star forming region that was specifically geared to the Taurus cloud. Details on the numerical implementation, on performance and convergence properties of the method, and tests against analytic models and other numerical schemes in the context of turbulent supersonic astrophysical flows can be found in Mac Low et al. (1998), Klessen & Burkert (2000, 2001) and Klessen et al. (2000).

This simulation has been performed without gravity until a particular, well defined elongated structure is formed. We then turn-on self-gravity. This leads to localized collapse and a sparse cluster of protostellar cores builds up. Timescale and spatial distribution are



**Fig. 1.** Evolution of the column density of an SPH simulation. The filament in the first frame (before self-gravity is turned-on) shows that turbulence is responsible in forming this kind of structures. The small bar in the bottom-left of each frame denotes the Jeans length (equation 1) at this time. At later times, self-gravity is turned on and the filament suffers gravitational fragmentation on a free-fall timescale (equation 2).

in good agreement with the Hartmann (2002) findings in Taurus. For illustration, we show eight column density frames of the simulation in figure 1. The first frame shows the structure just before self-gravity is turned-on, and we note that the filament forms cores in a fraction of Myr. The timestep between frames is 0.1 Myr. The mean surface density for the filament is  $0.033 \text{ g cm}^{-2}$ , corresponding to a visual extinction of  $\sim 7.5$ . Using equations 1 and 2 this value gives a Jeans length of  $\lambda_J \sim 0.2 \text{ pc}$ , and a collapsing timescale of  $\tau \sim 0.5 \text{ Myr}$ . Note from figure 1 that the first cores appear roughly at  $\tau \sim 0.3 \text{ Myr}$ , although the final structure of collapsed objects is clearly defined at  $t = 0.5 \text{ Myr}$ . The typical separation between protostellar cores (black dots in figure 1) is about the Jeans length  $\lambda_J$ .

This example demonstrates that indeed turbulence is able to produce a strongly filamentary structure and that at some point gravity takes over to form collapsing objects, the protostars. However, the situation is quite complex. Just like in Taurus, the filament in figure 1 is not a perfect cylinder, the collapsed objects are not perfectly equally spaced as predicted by idealized theory, and protostars do not form simultaneously but during a range of times (between

$t \approx 0.3$  and  $0.6$  Myr). Even though the theory of gravitational fragmentation of a cylinder appears roughly, it becomes clear that the properties of the star forming region not only depend on the conditions set initially but are influenced by the large-scale turbulent flow during the entire evolution. Gravoturbulent fragmentation is a continuous process that shapes the accretion history of each protostar in a stochastic manner (e.g. Klessen 2001a).

#### 4. Mass Spectra of Clumps and Protostellar Cores

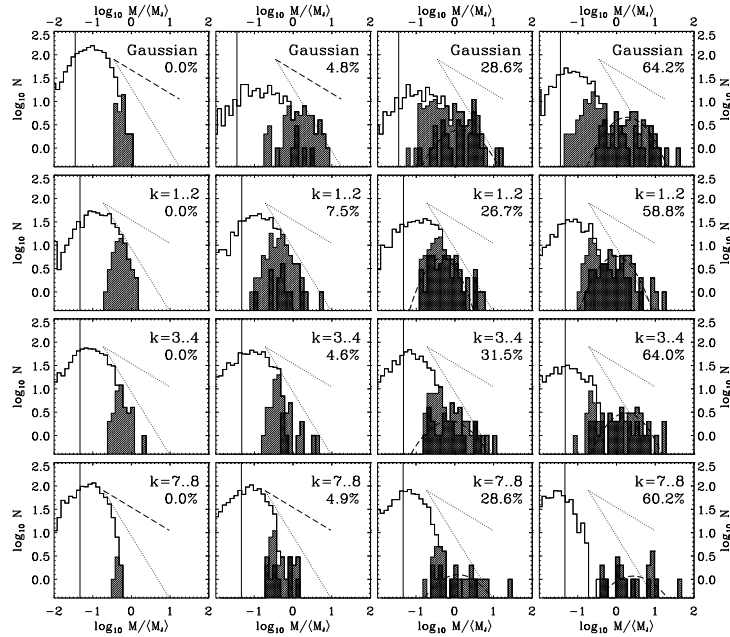
The dominant parameter determining stellar evolution is the mass. We discuss now how the final stellar masses may depend on the gravoturbulent fragmentation process, and analyze four numerical models which span the full parameter range from strongly clustered to very isolated star formation (for full detail see Klessen 2001b).

Figure 2 plots the mass distribution of all gas clumps, of the subset of Jeans critical clumps, and of collapsed cores. We show four different evolutionary phases, initially just when gravity is ‘switched on’, and after turbulent fragmentation has lead to the accumulation of  $M_* \approx 5\%$ ,  $M_* \approx 30\%$  and  $M_* \approx 60\%$  of the total mass in protostars.

In the completely pre-stellar phase the clump mass spectrum is very steep (about Salpeter slope or less) at the high-mass end. It has a break and gets shallower below  $M \approx 0.4 \langle M_J \rangle$  with slope  $-1.5$ . The spectrum strongly declines beyond the SPH resolution limit. Individual clumps are hardly more massive than a few  $\langle M_J \rangle$ .

Taking gravitational evolution into account modifies the distribution of clump masses considerably. As clumps merge and grow bigger, the spectrum becomes flatter and extends towards larger masses. Consequently the number of cores that exceed the Jeans limit increases. This is most evident in the Gaussian model of decayed turbulence, the clump mass spectrum exhibits a slope  $-1.5$ .

The mass spectrum depends on the wavelength of the dominant velocity modes. Small-scale turbulence does not allow for massive, coherent and strongly-selfgravitating structures, and together with the short interval between shock passages, this prohibits efficient merging and the build up of a large number of massive clumps. Only few clumps become Jeans unstable and collapse to form stars. This occurs at random locations and times. The clump mass spectrum remains steep as in the case without gravity. Increasing the driving wavelength leads to more coherent and rapid core formation, leading



**Fig. 2.** Mass spectra of protostars (hatched thick-lined histograms), of gas clumps (thin lines), and of the subset of Jeans unstable clumps (thin lines, hatched distribution). Different evolutionary phases are defined by the fraction of mass converted into protostars and are indicated in the upper right corner of each plot. Masses are binned logarithmically and normalized to the average Jeans mass  $\langle M_J \rangle$ . (From Klessen 2001b.)

to a larger number of cores.

Long-wavelength turbulence or turbulent decay produces a core mass spectrum that is well approximated by a *log-normal*. It roughly peaks at the *average thermal Jeans mass*  $\langle M_J \rangle$  of the system (see Klessen & Burkert 2000, 2001) and is comparable in width with the observed IMF (Kroupa 2002). The log-normal shape of the mass distribution may be explained by invoking the central limit theorem (e.g. Zinnecker 1984), as protostellar cores form and evolve through a sequence of highly stochastic events (resulting from supersonic turbulence and/or competitive accretion).

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